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# The Impacts of Using Augmented Reality to Support Aircraft Maintenance

Terry R. Hebert Jr.

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**THE IMPACTS OF USING AUGMENTED REALITY TO SUPPORT AIRCRAFT  
MAINTENANCE**

THESIS

Terry R. Hebert Jr., Captain, USAF

AFIT-ENS-MS-19-M-121

**DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY**

**AIR FORCE INSTITUTE OF TECHNOLOGY**

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**Wright-Patterson Air Force Base, Ohio**

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THE IMPACTS OF USING AUGMENTED REALITY TO SUPPORT AIRCRAFT  
MAINTENANCE

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

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Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Logistics Supply Chain Management

Terry R. Hebert Jr., BS

Captain, USAF

March 2019

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THE IMPACTS OF USING AUGMENTED REALITY TO SUPPORT AIRCRAFT  
MAINTENANCE

Terry R. Hebert Jr., BS

Captain, USAF

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## **Abstract**

The United States Air Force (USAF) expends significant resources to address the rise in aviation mishaps derived from an overworked, understaffed maintenance community, and high operational environment. Currently, paper-based technical orders (T.O.) are utilized by maintainers to accomplish aircraft inspections, servicing, and maintenance tasks. As technology advances, many civilian agencies have begun to leverage augmented reality (AR) to improve organizational proficiency. This research seeks to identify if the inclusion of AR within aircraft maintenance will positively or negatively affect maintenance task accuracy and completion time. A single variable randomized complete block design (RCBD), within-subject design of experiment (DOE) assesses the differences between a treatment group (AR-enabled T.O.) contrary to the control group (paper-based T.O.). Results conclude AR-enabled T.O.s designed from the AF perspective will reduce simple task errors, but will not impact total task completion time. Differentiation from prior findings, application specificity, will impact AR effectiveness and utilization within the organization employed. Additionally, experimental research revealed the need to address current AF infrastructure barriers before implementation of the technology within the organization.

*Above all, I thank God for giving me the strength, knowledge, and perseverance to accomplish this research, may all glory be yours. My wife for her unwavering support and ability to inspire me to attain heights I never thought possible. My children for their understanding and cooperation in my absence. Finally, thank you Col Paul Filcek for your mentorship and support as I labored through the AFIT program, it's an experience I will never forget.*

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Terry R. Hebert Jr.



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# **THE IMPACTS OF USING AUGMENTED REALITY TO SUPPORT AIRCRAFT MAINTENANCE**

## **I. Introduction**

### **General Issue**

From its first conflict with Mexico in 1920, the Army Air Corps realized adequately maintained aircraft and the ability to sustain maintenance would be two essential factors for future operational success. However, the cost of sustainment remains high as maintainers often sacrifice quality of life and endure long, arduous shifts to achieve this goal (Department of the Air Force, 2017). Unfortunately, as the Air Force (AF) continues to evolve from its early Air Corps era and incorporate technology within its organization, the utilization of legacy aircraft past their intended service life remains a reality and ultimately increases fleet complexity. With no reduction of pace imminent as depicted amidst the recently added KC-46 Pegasus to a fleet encompassing the B-52 Stratofortress, and scheduled to maintain operational status well into 2040, an already wide-ranged age gap will continue to expand further compounding this complexity (Slanchik, 2019; Swarts, 2016). Although aircraft diversity increases AF operational capabilities, it confounds maintenance personnel, which leads to inadequate training, overworked maintainers, and manning shortages that may result in fewer fully mission capable (FMC) aircraft to support the mission (Woody, 2017).

AF leaders have attempted to rectify the identified maintenance issues through improved technical guidance, maintenance training, Air Force specialty code (AFSC)

designation removal (for craftsman level maintainers), continuous process improvement (CPI) concepts, aircraft fleet reduction initiatives, and increased maintenance personnel levels. However, with unsustainable success attributable to unforeseen variability, the AF finds themselves in the midst of another aircraft maintainer shortage (Barber, 2017).

Recently, an attempt has been made to address the shortage through increased manning levels, but training for a new accession to attain the 5- skill level (journeyman) may take up to two years depending upon AFSC and aircraft designation (Department of the Air Force, 2019). Further, each new accession assigned to a 5- or 7-level trainer reduces his or her time available to work the operational mission. Unfortunately, with no foreseeable decline in an already high operational tempo environment and deterioration of available aircraft maintainers, the AF can no longer afford to complete a training regimen designed to last up to two years (Woody, 2017). Subsequently, the environment has created its own expedited training regimen. An atmosphere where maintainers train and certify on tasks through the interpretation of maintenance manuals while electing to forgo the hands-on portion of a training process. Without the critical aspect of component removal and installation, trainers are unable to validate training comprehension and retention adequately. Consequently, degradation in proficiency and repair times surmount, which drive up maintenance mishaps and overall aircraft sustainment cost (Losey, 2017). In response, AF leaders have inquired about immersive technology, specifically augmented reality (AR), and its expected positive impact to Technical Order (T.O.) clarity and understanding as it fortifies linguistic communication with additional spatial cues (Knee, 2019).

Currently, T.O.s are available in either a paper or digital format and contain identical information to complete a task. Although the advancement from paper-based to digital has provided some modern convenience and ease of use features, the ultimate goal of increased quality remains to be actualized as maintenance mishaps have continued to rise over the past seven years (Losey, 2018), as shown in Figure 1. With the increase of mishaps, AF leaders continually assess technological advancements with the hope it improves communication within maintenance. Unlike previous attempts, organizations across the AF have looked toward private industry's advancements within immersive technology and its potential ability to increase task quality while reducing task time (Abraham and Annunziata, 2017).

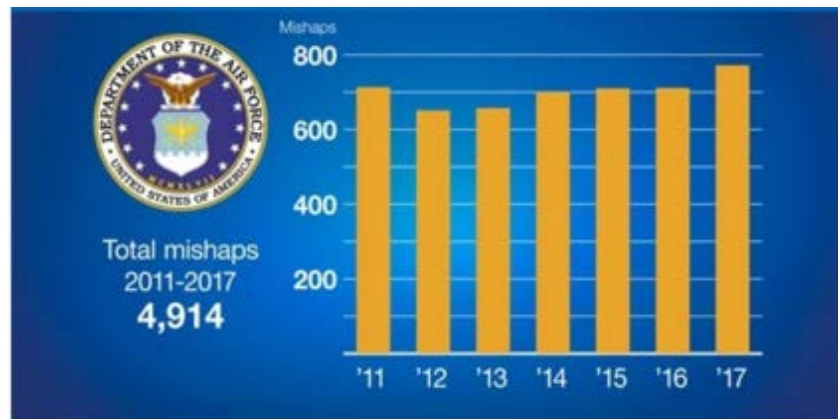


Figure 1. Air Force Aviation Mishaps (Losey, 2018)

Subsequently, organizations within the AF have begun to acquire mixed reality (MR) devices replicable to the civilian sector with the expectation that their organization will produce results comparable to their civilian counterparts. Although the employment of new technology has brought the AF to new heights, aircraft maintenance is a highly structured, restricted, and a process-oriented environment where one misstep could cost a life. Therefore, by design, a T.O. must be clear and concise to ensure accuracy and



reliability and reduce maintainer variability. These unique attributes make it extremely difficult for the AF to employ the same technology and expect minimal variation to the outcome. However, with only a promising outlook, the AF has already employed AR technology within training environments (Knee, 2019). Unfortunately, the actualized certainty of improved performance is not guaranteed, and to employ an unvalidated technology as it pertains to our unique environment may hinder the maintenance community instead of aiding it, as many maintainers have come to expect (Army Research Laboratory, 2019).

### **Problem Statement**

Due to a high operational tempo, the pressure to perform, and a rapidly evolving technological industry, the AF needs to adopt new ways to operate, especially in the aircraft maintenance environment.

### **Research Objectives/Questions/Hypotheses**

Will technicians perform a maintenance task better when using an AR-enabled T.O. than when using a traditional paper-based T.O.?

### **Investigative Questions**

1. Will using an AR-enabled T.O. assist technicians in decreasing maintenance task time?
2. What are the differences, if any, between using the AR-enabled T.O. and the paper-based T.O.?
3. Will using an AR-enabled T.O. assist technicians in increasing maintenance quality?

4. What are the differences, if any, between using the AR-enabled T.O. and the paper-based T.O.?

### **Methodology**

This Design of Experiments (DOE) study seeks to replicate a simple maintenance task within a controlled environment to capture an outcome from the effects of an introduced variable (AR). Evaluation of the two investigative questions was accomplished through a single variable-controlled experiment conducted at Wright-Patterson AFB, OH. The controlled design enabled assessment of an AR device and its impact on a simple maintenance task while limiting outside variables. The physical task resembled two-level AF aircraft maintenance task with both the written and AR instructions representative of an official AF T.O. Personnel selected to perform the task were all volunteers and qualified (via demographics questionnaire) for the experiment through prerequisites set forth by AF enlistment criteria. A total of 25 experiments were completed to generate the amount of data needed to ensure validity and reliability. Upon experimental completion, errors and task time were categorized per AF maintenance operational procedures. Finally, an Analysis of Variance (ANOVA) was employed to assess any statistical significance of a participant's generated errors and task time through traditional and AR instructed task, while a correlation matrix recognized any possible correlating demographic factors that may have influenced ANOVA results.

### **Limitations/Assumptions**

Currently, AF security concerns, network restriction, aircraft availability, maintenance personnel availability, and utilization of unsecured civilian hardware and software devices limited the feasibility to perform an actual aircraft maintenance task

defined in an operational T.O. Therefore, the experiment employed individuals outside of the maintenance community with a mock task to replicate a process one might encounter in maintenance. By using individuals other than AF enlisted maintenance personnel, verification of a baseline maintenance aptitude could not be attained through the Armed Services Vocational Aptitude Battery (ASVAB) test (Military.com, 2019). Further, the task selected was not an actual maintenance task. Subsequently, the broader-scoped and less stringent individual requirement may lead to a higher degree of data output generalization, while a limited scoped task may not capture all errors an individual might encounter as they perform a task. Consequently, the assumptions conclude that the sample population, T.O., and experimental task are representative of a maintenance task and the participants will abide by the experimental rules with no bias.

### **Implications**

Experimental results of this study may be used to inform military leaders and organizational level managers what impacts AR might have on a maintenance task. Specifically, this research will identify whether or not an AR-enabled T.O. will improve task completion time and quality. The results will determine if the integration of AR within maintenance is worth the pursuit, thus providing leaders with accurate information for managing AR resources effectively and accurately.

### **Preview**

This chapter summarized the background, problem statement, research questions, investigative questions, methodology, limitations, and outcomes and implications associated with this research into AR in AF aircraft maintenance. Subsequently, Chapter II defines AR, expand on the theoretical lens and discuss related literature; Chapter III

describes the methodology used to collect data via experiment, whereas chapter IV describes the data analysis and results. Finally, Chapter V presents discussion of the findings, conclusions, recommendations, and identify future research areas.

## **II. Literature Review**

### **Chapter Overview**

This chapter establishes the foundational framework for AR; its application through industry and the DoD to establish how its inclusion within the AF may affect aircraft maintenance. Through a common understanding of AR, its capabilities and rapid industrial growth, managers may then begin to conceptualize the use of this technology throughout their organizations. Explicitly, this literature distinguishes AR from other forms of immersive technology, identifies the possible benefits of AR over actual applications, and applies a resource-based view (RBV) to assess suitable applications.

### **Description**

Over the past 50 years, human interaction and dependency on technology continue to increase rapidly. As technology continues to evolve, bodily interaction begins to transfer into the immersive realm where the lines of physical reality begin to blur with the digital realm (Suh and Prophet, 2018). A broad concept, immersive technology describes the overarching constructs of three primary facets within the digital realm; mixed, augmented and virtual realities. Although each reality focuses on a different aspect of immersive technology, each facet closely relates to one another and has attributed to the convolution of definitions within the industry (Angelopoulos, 2018). Immersive technology populates the space between both the physical and digital realm (Milgram and others, 1994). Therefore, each facet for immersive technology augmented, virtual, and mixed reality defined are “experiences that overlay graphics on video streams of the physical world are augmented reality, the experiences that occlude your view to present a digital experience are virtual reality, and the experiences enabled between these

two extremes is a mixed reality” (Bray and others, 2018). Figure 2 depicts the mixed reality spectrum. A foundational component of this experiment, utilization of digital overlays on a physical world through enhanced videography concludes that the platform for this experiment is augmented reality (AR).

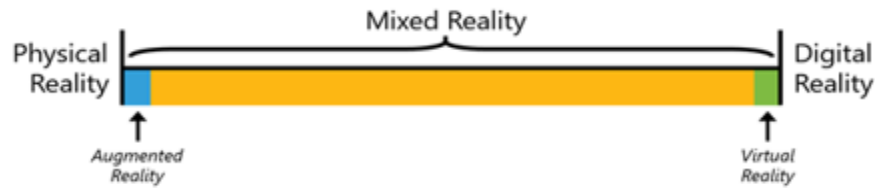


Figure 2. Mixed Reality Spectrum (Bray and others, 2018)

### **Resource-Based View**

Both tangible and intangible, resources and their successful management can significantly impact an organization (Wicker and Breuer, 2013). Although all resources within an organization are essential, the resource-based view (RBV) construct, categorizes resources as either common or strategic (Edwards, 2013). Common resources are those that are readily available to a competitor, while strategic resources are assets classified as valuable, rare, difficult to imitate, and not substitutable (Edwards, 2013). Therefore, due to its unique characteristics, a correctly utilized strategic resource give organizations a competitive advantage over their rivals through increasing value in a way that rivals cannot (Barney, 1991).

In today’s society, many iterations of technology (computers, phones, tablets) are considered common resources throughout multiple organizations. However, AR’s strategic attributes raise the technological bar as it displays various layers of instructional information to enrich an individual’s environment as they move toward a common

organizational goal (Hulett, 2019). Although inimitable and expensive to employ, larger industries have developed specific operational methods for AR and are beginning to capture productivity improvements ranging upwards of 40% from its implementation (Boeing, 2018). A procedure the AF should employ to ensure their implementation of this strategic resource becomes a success (Gilbert, 2016).

### **Relevant Research**

From early on, organizations believed the application of technology within the correct construct could increase organizational productivity (Jaffe and others, 1982). However, utilization of immersive technology to improve individual performances did not manifest until early 1990 when researchers discovered virtual fixtures, sensory information, and haptic feedback could improve an individual's performance by up to 70% (Rosenberg, 1992). Although successful, the effectiveness of AR remained in question until Tang and others (2003) dispersed 75 university students amongst 4 treatment groups: printed media, computer-assisted instruction (CAI) on liquid crystal display (LCD) monitors, CAI on see-through head-mounted displays (HMD), and spatially registered AR through HMD (Tang and others, 2003). Results illustrate each treatment group and a positive effect on accuracy, and cognitive load, as shown in Figure 3, of an individual's mental workload as defined by the NASA Task Load Index (TLX). As the usability of AR within the civilian sector continued to grow through experimental

testing, the feasibility of utilizing this technology within the DoD and the maintenance environment remained in question.

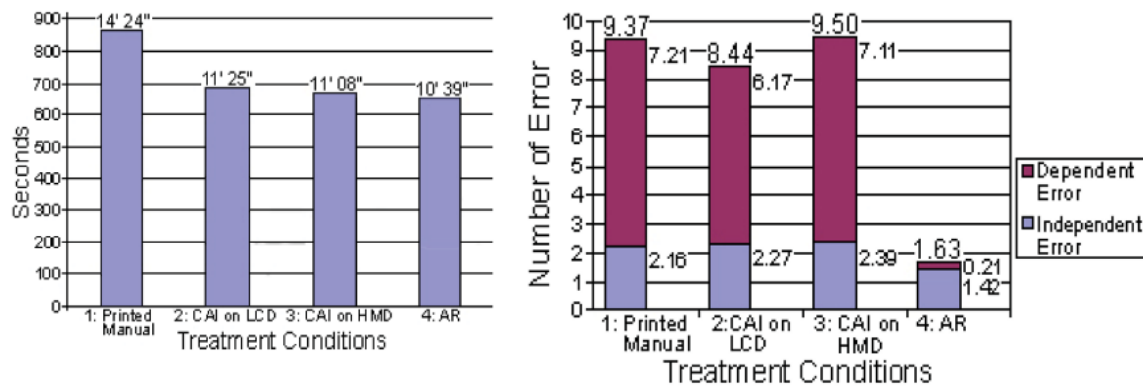


Figure 3. Average Time of Completion and Number of Errors in Each Treatment (Tang and others, 1992)

Shortly after successful demonstration of AR mobility through HMD utilization, the aircraft maintenance industry identified possible areas where AR would succeed in reducing errors, and task time through readily accessible instructional methods and superimposed images to guide technicians through a task (Haritos and Macchiarella, 2005). With the continued emergence of AR, entities of the DoD, specifically the U.S. Marine Corps tested the technology on the LAV-25A1 armored personnel carrier turret and their maintainers (Henderson and Feiner, 2011). The results showed that task completion, localization time, and head movement improved, but could not support an increase in task accuracy. Similarly, Angelopoulos (2018) examined the effects of AR on efficiency and precision with 34 USMC personnel cued with AR as the only treatment. Each Marine completed a set of five tasks; the first three comprised of part placement and time while task four and five increased complexity through part assembly and increasing the distance of reference materials. The results suggest that AR can positively affect



efficiency, precision multiplied by completion time (Angelopoulos, 2018). These results are shown in Table 1.

Table 1. Efficiency Statistics (Angelopoulos, 2018)

	Error Type	95% Confidence Interval		P Value	Condition Advantage
Task 1	Absolute	4313.24	10432.18	<0.0001	ARC
Task 2	Cumulative	3197.59	9930.9	<0.0001	ARC
Task 3	Absolute Referential	3009.2	5507.2	<0.0001	ARC
Task 4	Complexity (Placement – Total Completion Time)	34676.28	40540.03	<0.0001	ARC
Task 4	Complexity (Placement – Placement Only Time)	1072.81	2863.63	<0.0001	ARC
Task 5	Complexity (Assembly)	8.264	166.15	0.0315	ARC

This current research differs from past experiments in four ways. It is the first known application of a one task within-subject DOE using AR as the single variable. A comparison from the AF perspective will analyze the total amount of maintenance errors and task time generated through the current T.O. media method, and an AR instructed media method. The utilization of Microsoft HoloLens (HL) HMD addresses prior restricted mobility concerns through its wireless design (Henderson and Feiner, 2007). Finally, with differentiating task error results in past trials, this experiment will attempt to clarify any potential effects AR may employ within the AF aircraft maintenance arena (Henderson and Feiner, 2011; Tang and others, 2003).

## Hypotheses

During component installation, errors of a task may manifest via an incorrect part sequence, selection, installation, or orientation. If AR sequentially displays information

and reduces the ambiguity of part placement through visual cues, it is reasonable to suspect that total discrepancies should decrease. Therefore:

**Hypothesis 1:** The introduction of an AR-enabled T.O. for a simple AF aircraft maintenance will significantly decrease total discrepancies when compared to current paper-based T.O. devices.

AR is purported to assist users in completing tasks quicker because it enables visual cues and eases access to information. Therefore:

**Hypothesis 2:** The introduction of an AR-enabled T.O. for a simple AF aircraft maintenance task will significantly decrease completion time when compared to using current paper-based T.O.s.

## **Summary**

The literature reviewed defined immersive technology and the three primary facets of this technology. Immersive technology and its potential impacts were observed through the RBV to highlight the potential competitive advantages that might be attained through the proper application of this technology. Finally, prior experimental procedures were examined to understand how the AF could test the technology when subjected to their maintenance construct and ascertain if AR could improve maintenance accuracy as it decreases task time.

### **III. Methodology**

#### **Chapter Overview**

The objective of this research is to detect the effects of a traditionally prompted or an AR prompted maintenance task as it pertains to an individual's completion time, quality, and learning rate. This chapter first focuses on the experimental design to include a selection of methodology, subjects, and location. The chapter discussion then focuses on data collection and analysis methods.

#### **Experimental Approach**

AR is a relatively new and developing technology, a Design of Experiments (DOE) approach was employed to compare and contrast a maintainer's task performance with diverse instructional methods. This DOE was chosen for several reasons. First, an experiment performed in a controlled environment ensured that related climate factors remained constant, thereby reducing response variability. Second, the experiment-controlled environment ensured human interaction remained limited to the participant and evaluator thereby removing external interruptions, distractions and the possibility of confounding experimental results. Third, a single variable randomized complete block design (RCBD), within-subject DOE, helped variability, and errors introduced from individual differences (Montgomery, 2013). Fourth, an experiment helps compare one method of instruction to the another in the same environment with identical factors to gain an accurate assessment of which instructional method AR or traditional would improve an individual's performance. The experiment adhered to all Internal Review Board (IRB) requirements before experiment initiation; reference (Appendix E) for the memorandum and approval.

## Task Selection

The initial task design included genuine aircraft maintenance with AF maintainers. However, a Technical Order (T.O.) distribution statement “E,” destruction of the experimental site, Tyndall AFB, FL, and thesis time boundaries, required the researcher to generate a comparable task that resembled a simple AF maintenance task. Although simple, a representable task must include the fundamental element of simplicity through a concrete outline of the task inputs, outputs, processes, goals, time requirements and information presentation (Liu and Li, 2012). Therefore, task selection resulted in project four from the Elenco Snap Circuits Lights Kit (SLC-175) as it accurately characterized a simple maintenance task through multi-step, simplistic design, instructional method, and replicable attributes, as shown in Figure 4.

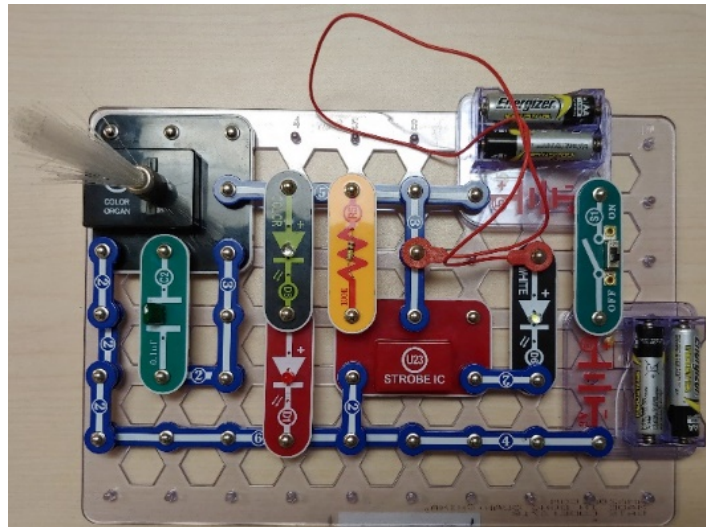


Figure 4. Elenco Snap Circuits Lights Kit, Project 4

Upon initiation of project four a participant would read all task instructions. Once understood, a participant would begin to build the project. By design, project assembly needed to be accomplished in sequential order. This approach led to the construction of a

four-level scheme with build validation stages located at the end of each level. A participant would move through the process as dictated by the T.O. as the evaluator tracked and annotated all T.O. deviations. After completion, a participant would wait approximately ten minutes before they began task two, the same project (unknown to the participant), but with the secondary instructional method.

### **Individual Selection**

Because the experiment is designed to gauge the outcomes of AR integration within the Air Force, participant requirements mirrored Air Force active duty enlisted personnel acceptance and retention criteria. To enlist in the Air Force an individual must meet three basic requirements; 1. Be between 17 and 39 years old, 2. Be a United States citizen or legal, permanent resident, and 3. Qualify for one of three educational tiers: Tier 1, Have a high school diploma, Tier 2, Attain a General Education Development (GED) with at least 15 college credits, or Tier 3, Obtain a GED (Powers, 2019; United States Air Force, 2019-b). Once qualified to enlist in the Air Force, limitations to an individual's service may not exceed 30 years if they attain the rank/grade of Chief Master Sergeant/E-9 (United States Air Force, 2019-a). Therefore, assuming equal opportunity to reach E-9, an eligible test subject must be between 17 – 69 years old, a United States citizen or legal, permanent resident, and reside in either educational tier 1, 2, or 3 to participate in the experiment.

Although the experiment focused on testing aircraft maintainers, the constraining factors identified in task selection also affected personnel selection. Consequently, the deliberate attempt to utilize maintainers shifted to the Air Force Institute of Technology (AFIT) faculty, staff, and students due to accessibility, and adherence to experimental

qualification factors as outlined above. Participation notification was accomplished through official (AFIT) email communication channels and reached an approximate 154 individuals, of which 29 responded with the intent to participate. If a recipient expressed interest, a meeting with the researcher would take place before the experiment to review a demographics questionnaire (Appendix A). Along with validating a potential participants eligibility, the questionnaire captured participant's age, gender, education level, AFIT student status, military service, length of service, immersive technology experience, and preferred learning method. In addition to the demographics questionnaire, all participants validated voluntary participation and were instructed not to discuss any preliminary information attained until project completion. Once an individual agreed to all requirements and a review of the questionnaire was complete, an individual would then be deemed eligible for the experiment. To obtain a robust Analysis of Variance (ANOVA) model, a sample size of 25 participants were required for the experiment (Schmider and others, 2010), an element satisfied with the selection of the first 25 eligibles of 29 potential applicants.

### **T.O./Hardware/Software Selection**

To conduct a representative experiment, the tasks T.O. needed to replicate current AF standards. To ensure accuracy, the generated T.O. derived from the outline of T.O. 11B29-3-60-2 (Department of the Air Force, 2015), which was then put through five test experiments to ensure readability and actionability. However, selection of an immersive technology for the experiment required a hardware and software platform that must be capable of written T.O. replication and align with a product on the Air Force Research Laboratory's (AFRL) potential device list. When coupled with item availability, the

Microsoft HoloLens (Microsoft, 2016) and Manifest application (Taqtile, 2018) would sculpt an appropriate AR experiment platform. The generated T.O. was then inputted into the AR device and tested through five test experiments to ensure continuity and accuracy remained constant between instructional methods.

### **Microsoft HoloLens**

As the industry continues to expand within the immersive technology theater, Microsoft HoloLens, as shown in Figure 5, encompasses five key attributes that led to its selection as a potential AR device for AF maintenance instructional use, attributes include:

- Head-Mounted Display (HMD)
- Commercial Off-the-Shelf Availability
- Remote Assistance
- User Interface
- Software Adaptability



Figure 5. Microsoft HoloLens (Microsoft, 2016)

## Manifest Application Software

Taqtile, Manifest creator designed an application platform that enables the digital realm to interact with reality in a user-friendly environment, as shown in Figure 6. The result empowers the user to depict, comprehend and interact with a set of instructions for the task they are to perform. A feature proved critical when combined with the following attributes:

- Hands-Free Use
- Step-by-Step Instructional Method
- Digital Overlays
- Visual Cues

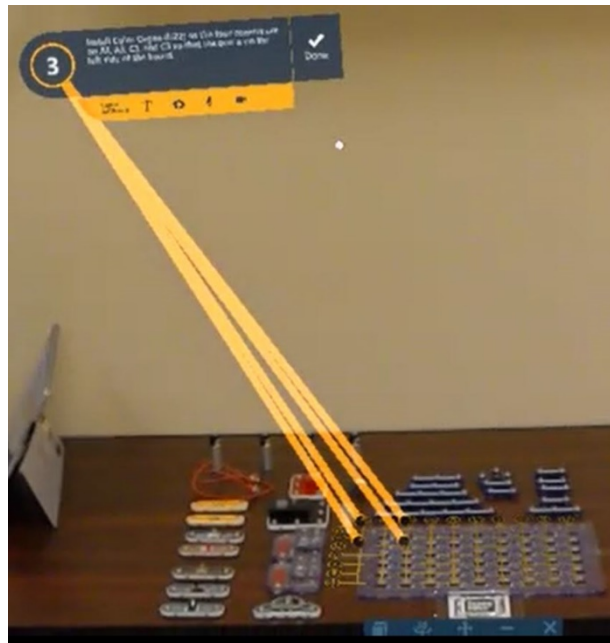


Figure 6. Manifest Software Instructional Overlay (Taqtile, 2018)



## **Experimental Design**

The experiment initiated on 13 December 2018 and concluded on 11 January 2019, with the location remaining constant at Wright-Patterson Air Force Base, Ohio. Upon arrival, an IRB abbreviated informed consent (Appendix F) informed the participant of all potential risk and the need to verbally agree to all terms and conditions before experiment initiation. Once finished satisfying all documentation requirements, identification of the first task was performed through Excel's random number generator function "`=Rand()`." A number returned within the range of 0.01 – 0.49 identified the T.O. instructional method would initiate the experiment followed by the AR instructional method. However, a number generated between 0.50 – 0.99 equated to task initiation via the AR instructional method followed by finishing the experiment with the T.O. instructed version of the task. With the instructional method order identification complete, instructions for each procedure was given to the participant before the initiation of a task. T.O. directives consisted of a two-slide PowerPoint presentation (Appendix G). Whereas the AR method required a participant to review a ten-slide PowerPoint presentation (Appendix H) and perform a "hands-on" AR tutorial. The tutorial familiarized a user with HoloLens, Manifest software, instructional method, system operation, and synchronized the AR environment as it pertained to each participant's physical attributes.

Once trained on the first task, initiation of the task began, and the participant would assemble the circuit board with instructions through all four levels, as shown in Figure 7. Upon completion of task one, participants would take a mandated ten-minute break while the evaluator verified all errors and prepared the circuit board for the second

task. When the participant returned, instructions for the second tasked method would commence. Once a participant understood the second instructional method, task two would begin and finish when the participant informed the evaluator of project completion. Finally, to complete each task, a participant would perform an operational check of the task when instructed by the evaluator to ensure proper assembly of the device.

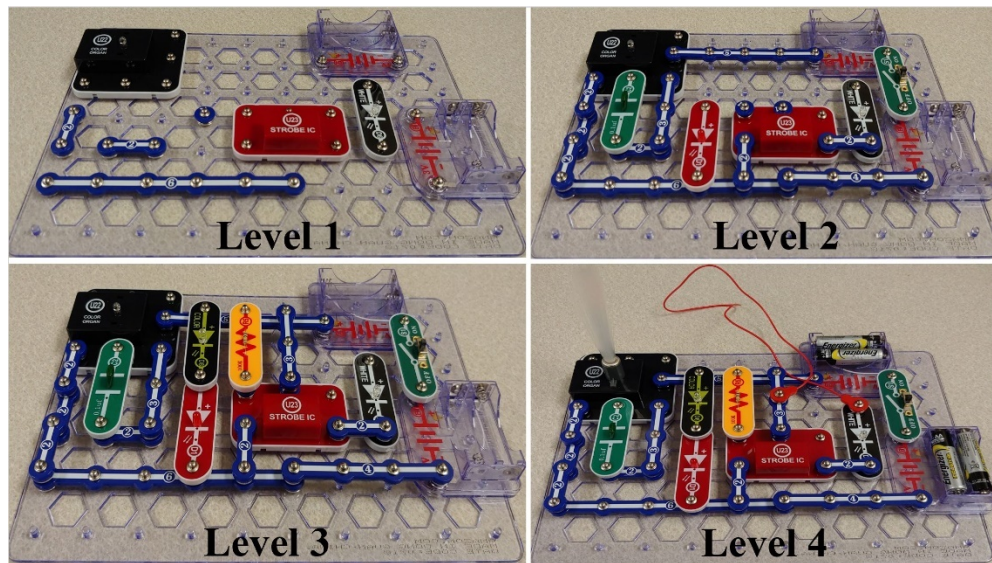


Figure 7. Assembly Level 1-4

Performance measurements included total task time and maintenance quality. Total task time is the amount of time an individual took to complete each assigned task. Time began when the evaluator said “begin” and finished when an individual proclaimed, they were “finished/done.” However, within the AF, a Maintenance Group (MXG) Commander defines task quality with a localized Maintenance Standardization and Evaluation Plan (MSEP). To address this specificity, a senior enlisted consultant who has over 19 years of experience as a metal’s technology technician, with two of those years spent as a Quality Assurance evaluator was consulted. His experience combined with the

author's 13 years of Dedicated Crew Chief experience, and guided by the Ramstein MSEP, led to the identification of five error categories as identified in Table 2. To evaluate errors and assess task quality, the evaluator conducted an "over the shoulder" evaluation. Equivalent to an Air Force Quality Verification Inspection (QVI), the assessment ensured proper assembly order and installation of parts on a participant's first attempt for all 31 actionable steps within the task. The QVI approach combined with a final task evaluation ensured all deviations from either instructional method were captured and annotated as they pertained to each error group.

Table 2. Error Categories

Participant #	Item Installation Incorrect	Incorrect Item Installed	Cautionary Procedure not Accomplished	Item not Installed	Order of Installation	Total Discrepancies
1	2	1	0	0	0	3
2	4	0	0	0	0	4
3	1	0	0	0	0	1
4	5	0	0	0	1	6
5	1	0	0	0	0	1

## Summary

Understanding the impacts of new technology on a deep-rooted process equips decision-makers with the knowledge of how that technology may affect their workforce. This chapter clarifies the strategy, choices, and execution procedures selected for the experiment. It clarifies why the task, personnel, location, and evaluation criteria while accurately identifying both independent and dependent experiment variables. Proper data analysis/interpretation begins with proper data collection, a mission this experiment aimed to achieve.

## IV. Analysis and Results

### Chapter Overview

This chapter discusses the DOE data collection and analysis procedures. Alongside answering the investigative questions, an analysis of each contributor to the total discrepancy category further specifies what traits of a task are affected the most by AR. Finally, a one-way ANOVA analysis was used for hypothesis testing, identifying areas of statistical significance at the 0.05 level.

### Data Collection

The single variable RCBD, within-subject DOE captured task data from 25 participants, while the demographics questionnaire captured their attributes. All 25 participants accomplished both instructional methods and generated the applicable data with regards to task time and errors, as shown in Table 3. Although the experiment achieved its goal of data collected from 25 participants, the initial analysis of data identified participant seven as an outlier for all measured categories for the first task and within normality for the second. Additionally, participant seven showed signs of confusion while constructing level one and stated: “that is what it meant when it said snaps into place.” Therefore, comprehension was determined to be the underlining factor of participant seven’s data anomalies resulting in the exclusion of their data from experimental results.

Table 3. Total Discrepancies by Category

	Item	Cautionary		Total Discrepancies		Total Discrepancies		Total Time (ss)
	Installation Incorrect	Incorrect Item Installed	Procedure not Accomplished	Item not Installed	Order of Installation	Total Discrepancies	Excluding Sequential Errors	
T.O.	48	5	0	0	9	63	53	17898
AR	26	2	1	1	3	33	30	18519
Total	74	7	1	1	12	96	83	36417

## **Data Analysis**

With data captured, categorization of the task and demographic information followed, reference (Appendix I). Once categorized, a correlation matrix conducted in Excel 2016 identified any possible characteristics of an individual that may have influenced task results. Finally, a one-way ANOVA analysis in JMP Pro 2013 provided all statistical calculations, boxplots, and histograms. The validity of using the data derived from 24 participants were assessed using a robust fittest within JMP combined with treatment effect size calculations. The robustness test indicated the absence of normality at a 0.05 significance level (SAS Institute Inc, 2019). Additionally, Cohen's d effect size model validated experimental significance with 24 participants through the determination if the treatment method had either a small ( $x > 0.2$ ), medium ( $x > 0.5$ ), or large ( $x > 0.8$ ) effect on the treatment group compared to the control group (Cooper, H. and Hedges, 1994).

## **Results**

A correlation table identified no significant correlations between the dependent variables (item installation incorrect, incorrect item installed, cautionary procedure not accomplished, item not installed, order of installation, total errors, and total time) and independent variables (group, masters, doctorate, physical, visual, verbal, solitary, and gender), as shown in Table 4.

Table 4. Correlation Table

	Item Installation Incorrect	Incorrect Item Installed	Cautionary Procedure not Accomplished	Item not Installed	Order of Installation	Total Discrepancies	Total Time (ss)
Group	-0.305	-0.126	0.146	0.146	-0.129	-0.310	-0.036
Masters	0.393	-0.218	-0.084	0.253	-0.025	0.310	0.291
Doctorate	-0.021	-0.114	-0.044	-0.044	-0.116	-0.075	0.006
Physical	-0.095	0.509	0.253	-0.084	0.173	0.072	-0.186
Visual	0.179	-0.447	-0.173	0.123	-0.022	0.063	0.237
Audio	0.015	-0.079	-0.030	-0.030	-0.081	-0.026	-0.011
Verbal	-0.106	-0.114	-0.044	-0.044	-0.116	-0.150	-0.135
Solitary	-0.103	0.236	-0.030	-0.030	-0.081	-0.078	0.016
Gender	0.041	-0.095	0.159	-0.134	-0.269	-0.031	0.186
Immersive Technology	-0.058	-0.104	-0.094	-0.094	-0.248	-0.148	-0.179

Total errors captured all errors a participant made as they progressed through the defined task. The total error category encompassed all subsidiary error categories and identified if task completion was not accomplished in sequential order. If at any point a participant accomplished a step out of order an error would result. However, a maximum of only four errors could result from sequencing due to the nature of each steps dependency upon another and the opportunity for a participant to validate task accuracy through a validation step at the end of each assessed level.

As shown in Figure 8, the total error ANOVA model produced an f-value of 4.8936, a p-value of 0.0320, a robust fit value of 0.0320, and effect size value of 0.6386.

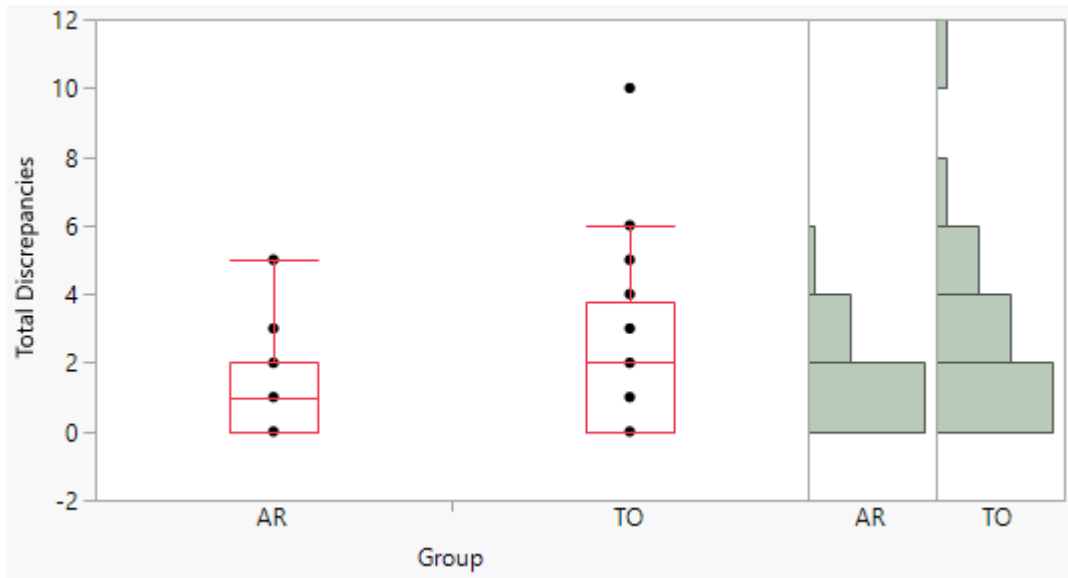


Figure 8. Boxplot and Histogram of Total Discrepancies and Treatment Group Data. F-value: 4.8936, P-value: 0.0320, Robust Fit: 0.0341, Effect Size: 0.6386

Total task time accounted for the accrued time from initiation to completion of a task. Task initiation began when the evaluator said “begin” and finished when the participant stated, “finish/done.” With a 0.0596 f-statistic, 0.8082 p-value, 0.9059 robust fit value, and 0.0705 effect size, the total time ANOVA model illustrated zero significance with the inclusion of AR in maintenance, as seen in Figure 9.

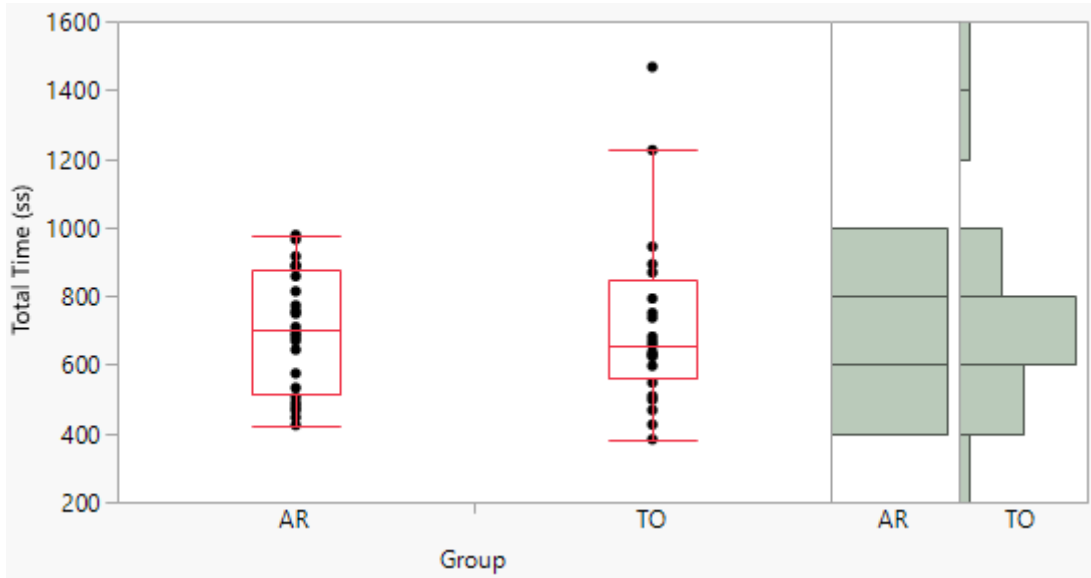


Figure 9. Boxplot and Histogram of Total Time (ss) and Treatment Group Data. F-value: 0.0596, P-value: 0.8082, Robust Fit: 0.9059, Effect Size: 0.0705.

## Hypotheses Results

Therefore, the results, as depicted in Table 5, provide evidence to support Hypothesis 1, which suggests that AR can reduce discrepancies during maintenance tasks. Consequently, Hypothesis 2, suggest AR inclusion within maintenance could reduce overall task time, could not be supported, as shown in Table 5.

Table 5. Hypotheses Results

Hypothesis	Supported?	Effect Size	Finding
$H_01$	Failed to Reject $H_01$	Medium	AR-enabled T.O. utilization will reduce simple task discrepancies when compared to traditional based T.O.s.
$H_02$	Reject $H_02$	Small	There is no difference in task time with the utilization of traditional based T.O.s and AR-enabled T.O.s to complete a simple task.



## Post-Hoc Analyses

With the answers for both investigative questions attained, further analysis of all total error following categories identifies how AR affects the specific attributes of a total error. Subsequently, the analysis depicted only one of the following error categories (parts installed incorrectly) as an affected factor of an AR-enabled T.O. A participant incorrectly installed apart when they finished their current step and proceeded to the next step identified through the removal of their hand from the recently installed part.

An ANOVA performed on parts installed incorrectly revealed high variation of treatment means, significant model design, and a medium treatment effect. However, the model failed to show significance at the 0.05 level but is trending toward significance with a p-value below 0.1 at 0.0670. Although above 0.05 the p-value below 0.1, a significant robust fittest, and medium effect size illustrates commonality with all other significantly impacted variables, validating ARs ability to reduce part installation errors, as seen in Figure 10.

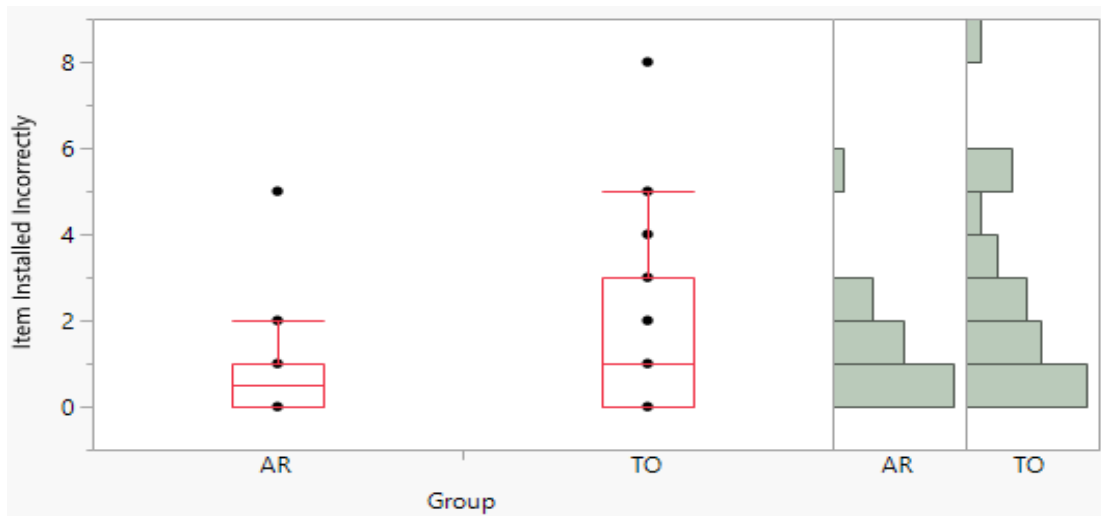


Figure 10. Boxplot and Histogram of Item Installed Incorrectly and Treatment Group Data. F-value: 4.8936, P-value: 0.0670, Robust Fit: 0.0341, Effect Size: 0.6274.

Finally, an analysis was performed on total discrepancies where task completion did not depend on the order of part installation. Therefore, all sequential order errors were removed from the total discrepancy category and identified AR-enabled T.O.s would also reduce non-sequential task errors. An f-value of 4.7693 suggests statistically significant variation within treatment group means at the  $p = 0.0341$  level. The effect size is 0.6304, and a robust fit value of 0.0238 indicates the normality assumption holds. Figure 11 illustrates the relationship between the treatment and control group.

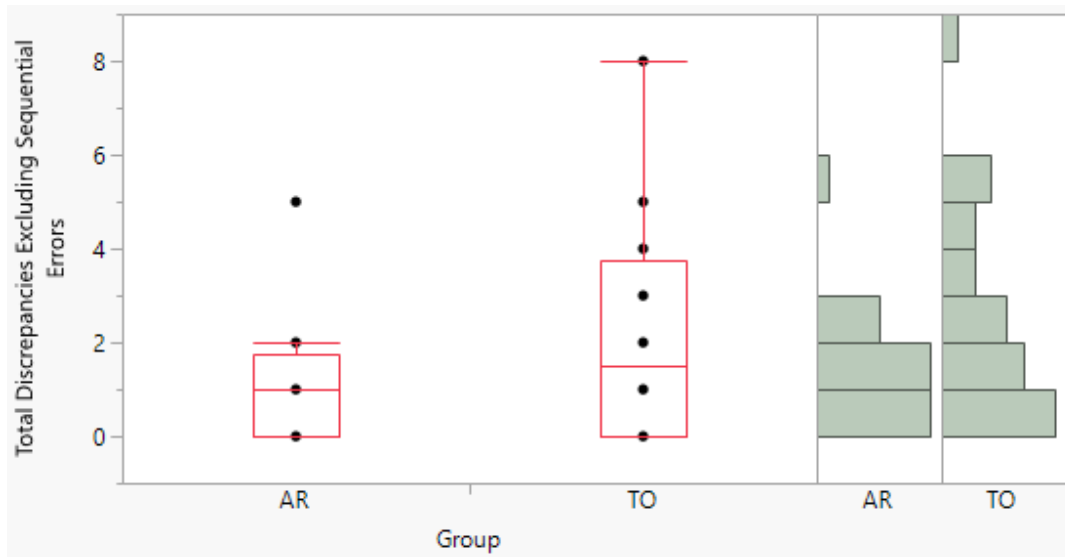


Figure 11. Boxplot and Histogram of Total Discrepancies Excluding Sequential Errors and Treatment Group

Data. F-value: 4.7693, P-value: 0.0341, Robust Fit: 0.0238, Effect Size: 0.6304.

## Summary

Overall, the results suggest that the inclusion of AR-enabled T.O.s within aircraft maintenance can reduce sequential, non-sequential, and part installation errors of a simple task. The results clarify the ability to attain task accuracy and validate earlier research discoveries by Tang and others (2003). However, contrary to Tang and others (2003) and utilization of this experimental construct, AR failed to prove useful with the

inability to reduce total maintenance task time. Although the results suggest AR is not a panacea, it can aid in the quality of maintenance a maintainer produces.

## **V. Conclusions and Recommendations**

### **Chapter Overview**

This chapter describes the findings in detail. Research conclusions analyze the data and the impacts of AR-enabled T.O.s on a simple maintenance task attainment of quality improvements and time reduction. Future work identifies areas of study that should be better understood to implement an AR-enabled T.O. successfully. Finally, recommendations will establish a way forward as maintenance continues to implement AR within their fundamental construct.

### **Discussion**

Ultimately, this research attempted to determine if the application of AR-enabled T.O.s within AF aircraft maintenance would improve task time and quality. The results suggest that AR could decrease task discrepancies thereby increasing quality for a simple aircraft maintenance task. However, the results failed to support the notion that an AR-enabled T.O. would decrease maintenance task completion time. Additionally, with a reduction in task discrepancies, the experiment identified not only a decrease in a step-by-step task but more generalized task where order specificity may not be a factor of task completion. The final maintenance task category effected from an application of this technology within maintenance through decreased errors manifested through the installation of parts.

Both this experiment and Tang and others (2003) center results on participants with no prior knowledge of the performed task whereas Henderson and Feiner (2011) utilize maintenance technicians as their participants, individuals who understand the tasks fundamentals through previous occupational training. The contrast of participants

advocates application of AR to commence within the maintenance training realm. An environment where individuals continually learn new task to enhance proficiency to reduce discrepancies.

However, unlike previous research, the experimental results attained from this experiment illustrate no decrease in task time with its inclusion. Currently, an AF T.O. is required to remain with the maintainer as they accomplish a task. Although hands-free, the utilization of AR in this experiment still required a technician to utilize their hands as they progressed through a task. An attribute that detracts from task accomplishment in the same manner a traditional T.O. does, hand utilization, possibly curable through voice recognition software.

Additionally, the experiment revealed that AR-enabled T.O.s could positively impact both sequential and non-sequential tasks. A fundamental aspect of maintenance, sequential tasks are utilized where safety is paramount for both the maintainer and the aircrew operating the aircraft. However, the majority of task in aircraft maintenance consist of non-sequential tasks. Therefore, AR inclusion within maintenance can expand to less crucial task comparable to aircraft inspections, and routine servicing where task accuracy is the priority.

Although the application of an AR-enabled T.O. would produce task benefits, experimental procedures highlighted multiple outside variables that could impact the application of this technology throughout the AF. From initial design, experimental success remained in question because of the AF wireless network. Although existent, connectivity issues forced utilization of a wireless hotspot to enable intercommunication between the HL, electronic display and the Taqtile server. Currently, AF digital T.O.s are

stored on the electronic device a technician utilizes to perform a task, this alleviates wireless network dependency as instructions are updated daily through a hardwired connection, a characteristic the HL may not be capable of accomplishing with only 54.09 gigabytes of storage and a vast T.O. library (Rubino, 2016). Additionally, security remained a liability with a T.O. distribution statement “E,” and the applications creator requirement to utilize their server as the primary storage device, an option not currently available for aircraft maintenance T.O.s.

It became apparent from the initiation of an IRB that there may be some slight adverse effects felt amongst participants. Although not often, a few individuals felt relief upon HL removal as they attempted to regain a sense of physical reality. However minor, the disorientation does bring up safety concerns with its utilization in the field. A highly volatile atmosphere where maintainers are introduced to risk every day, immersive technology may further convolute an already hazardous environment.

Further, instruction comprehension may not always be apparent. Participant seven illustrated the need for assistance from an experienced individual as they struggled through the first level of task one. A troubling aspect overcome once an understanding of the task was accomplished through proper part placement. At which point no similar errors were committed. A hindrance further identifying the need for intercommunication with maintenance and their craftsmen to alleviate any comprehension issues that may arise amongst inexperienced maintainers. Finally, as development of the maintenance task commenced, a once perceived simple design proved difficult to build within the digital realm. Although proper training alleviated the majority of tasks development

concerns, time to build a task exceed the researcher's expectations and required multiple attempts to ensure accuracy.

### **Recommendations for Action**

With continued divergence on immersive technology as the answer to improving maintenance quality and time, a better understanding of the expected benefits and implications of the technology need to be understood. Although the experimental results depict the inclusion of AR-enabled T.O. devices within maintenance would positively affect maintenance quality, it failed to prove the same technology would decrease the task time of a simple task. However, just as this experiment only tested one facet of a maintenance task, a multitude of maintenance applications still need to be analyzed to understand the full impact of this technology throughout maintenance. Additionally, the current AF infrastructure hinders seamless integration of the technology through organizations and needs rectification before AR may attain success. An important limiting factor the AF needs to address before integrating AR within aircraft maintenance.

### **Recommendations for Future Research**

From initiation to completion, the experiment encountered many barriers that had to be overcome to complete the research. First, an extremely restrictive AF network hindered the utilization of industry-leading software and hardware. Second, the hardware and software interface proved to be labor-intensive and required additional support from software developers to ensure content functionality. Third, individuals react differently to HMD and immersive technology devices and create additional safety with its application amongst physical reality. Fourth, attainment of information may not always be apparent,

and the ability to interact with experienced maintainers may ease the learning curve of the technology and the information it displays. Finally, the research conducted focused on one aspect of aircraft maintenance, part installation and did not account for other vital components of a successful maintenance organization; routine servicing, inspections, part removal, and fault isolation.

### **Summary**

This research concentrated on identifying the effects of AR integration within AF aircraft maintenance. Overall, the results depicted that AR would benefit maintenance as it increases maintenance quality of sequential task, non-sequential task, and part installation while ineffective at task time reduction. Although benefits may be actualized with the inclusion of AR, a current infrastructure designed around security may hinder full integration of this technology. A facet the AF must address to attain the full potential of this strategic resource.



## Appendix A: Demographics Questionnaire

Participant #: \_\_\_\_\_

1. What is your current age? \_\_\_\_\_
2. To which gender identity do you most identify?
  - a. Male
  - b. Female
  - c. Other
3. What is the highest degree or level of school you have completed? (If you're currently enrolled in school, please indicate the highest degree you have received).
  - a. Less than a high school diploma
  - b. High school degree or equivalent (e.g. GED)
  - c. Some college, no degree
  - d. Associate degree (e.g. AA, AS)
  - e. Bachelor's degree (e.g. BA, BS)
  - f. Master's degree (e.g. MA, MS, MEd)
  - g. Professional degree (e.g. MD, DDS, DVM)
  - h. Doctorate (e.g. PhD, EdD)
4. Have you ever been an AFIT Student?
  - a. Yes
  - b. No
5. Have you ever served in the Military?
  - a. Yes
  - b. No
6. If yes to question 5:
  - a. Which service? \_\_\_\_\_.
  - b. How long? \_\_\_\_\_.
  - c. Are you currently still in the service? Yes / No

7. Have you ever used immersive technology before (circle all that apply)? Virtual Reality / Augmented Reality / Mixed Reality.
8. Which learning methods do you prefer (circle one)? Visual / Audio / Verbal / Physical / Logical / Social / Solitary.

## Appendix B: Task Discrepancy Tracker

### T.O. Discrepancy Tracker

Participant #: \_\_\_\_\_

Random Number Generator #: \_\_\_\_\_

Subject will start with the (circle one) T.O. / M/R assembly method.

Date: \_\_\_\_\_, Start Time T.O.: \_\_\_\_\_, Stop Time T.O.: \_\_\_\_\_,

Total Time T.O.: \_\_\_\_\_

Skipped Steps:

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Operational Check Good: Yes / No

Supported 5-Snap Wire (cautionary note): Yes / No

Discrepancies, classification will be accomplished after project completion.

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## M/R Discrepancy Tracker

Participant #:\_\_\_\_\_

Start Time M/R: \_\_\_\_\_, Stop Time M/R: \_\_\_\_\_,

Total Time M/R: \_\_\_\_\_

Skipped Steps:

---

Operational Check Good: Yes / No

Supported 5-Snap Wire (cautionary note): Yes / No

Discrepancies, classification will be accomplished after project completion.

This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

# **TO Project 4 (Light Show)**

**TECHNICAL  
MANUAL WORK  
PACKAGE  
INTERMEDIATE MAINTENANCE  
INSTRUCTIONS WITH  
ILLUSTRATED PARTS BREAKDOWN**

**SNAP  
CIRCUTS  
MODEL:  
LIGHT,  
PROJECT 4 LIGHT SHOW**

General Information:

This Technical Order (T.O.) is a checklist item. The steps provided below shall be accomplished in sequential order, and you may not continue to the next step until its prior step has been completed.

1. Assembly:

Assembly contains instructions for complete assembly of the Light Show project. The procedures are arranged in a logical flow of component assembly. The assembly process will work through a four-level process beginning at level one with the final step concluding with the completion of level four. Installation of a component is achieved when the item snaps into place, and an audible “click” is heard. Refer to Figure 1 for a completed illustration of the Light Show Project.



During installation of a component, an audible “click” may not be heard. If no “click” is heard, ensure proper installation by slightly pulling up on the installed part. If installed incorrectly the part may/will move from its location. If installed correctly, the part will remain in the installed location.

1.1 Begin Assembly of Level One:

- 1.1.1 Install Color Organ (U22) so the four corners are on A1, A3, C1, and C3 so that the box is on the left side of the board.
- 1.1.2 Align the first Battery Holder (B1) on B7, and B9 so that the battery compartment faces the top of the board and install.
- 1.1.3 Align the second Battery Holder (B1) on D9, and F9 so that the battery compartment faces the right side of the board and install.
- 1.1.4 Install the Strobe IC (U23) so the four corners are on D5, D7, E5, and E7 so that the Strobe IC box is facing the bottom of the board.
- 1.1.5 Install the White Light Emitting Diode (D6) on C8, and E8 so that the arrow is pointing to the bottom of the board.
- 1.1.6 Install a 6-Snap Wire on F1 and F6.
- 1.1.7 Install a 2-Snap Wire on D1, and E1.
- 1.1.8 Install a 2-Snap Wire on E2, and E3.
- 1.1.9 Install a 1-Snap Wire on D4.
- 1.1.10 Validate the placement of all Level One components (see Figure 12) and then begin assembly of Level Two.

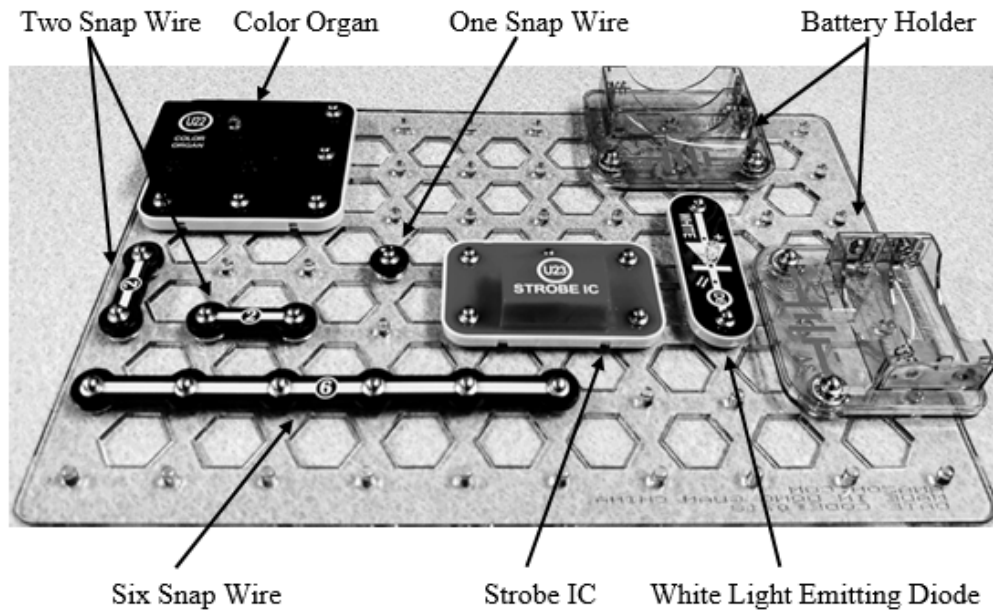


Figure 12. Completed Level One Example

## 1.2 Begin Assembly of Level Two:

- 1.2.1 Install the Red Light Emitting Diode (D1) on D4, and F4 so that the arrow is pointing to the bottom of the board.
- 1.2.2 Install the 0.1 $\mu$ F Capacitor (C2) on C2, and E2 so that the 0.1 $\mu$ F symbol towards the bottom of the board.
- 1.2.3 Install the Slide Switch (S1) on B9, and D9 so that the switch is toward the right side of the board.
- 1.2.4 Install a 5-Snap Wire on B3, and B7.
- 1.2.5 Install a 4-Snap Wire on F6, and F9.
- 1.2.6 Install a 3-Snap Wire on C3, and E3.
- 1.2.7 Install a 2-Snap Wire on C1, and D1.
- 1.2.8 Install a 2-Snap Wire on E1, and F1.
- 1.2.9 Install a 2-Snap Wire on E5, and F5.



- 1.2.10 Install a 2-Snap Wire on E7, and E8.
- 1.2.11 Install a 1-Snap Wire on D5.
- 1.2.12 Install a 1-Snap Wire on D6.
- 1.2.13 Validate the placement of all Level Two components (see Figure 13) and then begin assembly of Level Three.

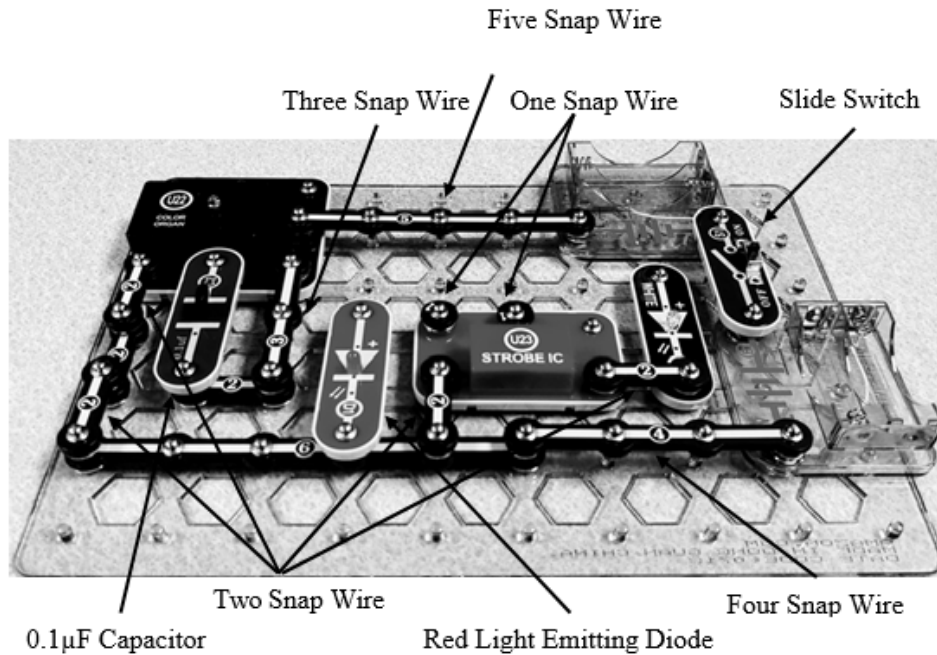


Figure 13. Completed Level two Example

1.3 Begin Assembly of Level Three:

- 1.3.1 Install the Color Light Emitting Diode (D8) on B4, and D4 so that the arrow is pointing to the bottom of the board.



The 5-Snap Wire must be supported underneath (with your finger) at location B5 prior to the installation of the 100k $\Omega$  Resistor (R5) on location B5. Failure to support the 5-Snap Wire could result in damage to, or destruction of equipment.

- 1.3.2 Install the 100k $\Omega$  Resistor (R5) on B5, and D5 so that the 100k symbol is toward the bottom of the board.
- 1.3.3 Install a 3-Snap Wire on B6, and D6.
- 1.3.4 Validate the placement of all Level Three components (see Figure 14) and then begin assembly of Level Three.

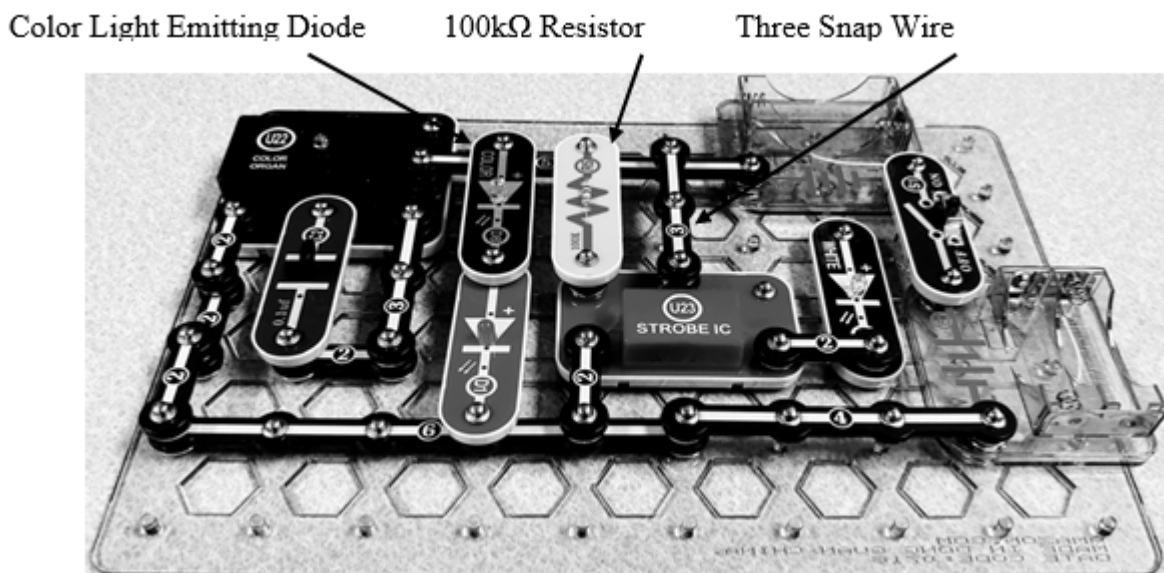


Figure 14. Completed Level Three Example

#### 1.4 Begin Assembly of Level Four:

- 1.4.1 Install the Jumper Wire (Red) on C6, and C8.
- 1.4.2 Install the Mounting Base (MB) in the Color Organ (U22).

- 1.4.3 Install the Fiber Optic Tree (FOT) in the Mounting Base.
- 1.4.4 Install the first battery in Battery Holder #1 (B1) so that the top battery's positive terminal is facing the right side of the board.
- 1.4.5 Install the second battery in Battery Holder #1 (B1) so that the bottom battery's positive terminal is facing the left side of the board.
- 1.4.6 Install the first battery in Battery Holder #2 (B1) so that the right battery's positive terminal is facing the bottom of the board.
- 1.4.7 Install the second battery in Battery Holder #2 (B1) so that the left battery's positive terminal is facing the top of the board.
- 1.4.8 Validate the placement of all Level Four components (see Figure 15) and then inform the proctor you have completed the experiment.

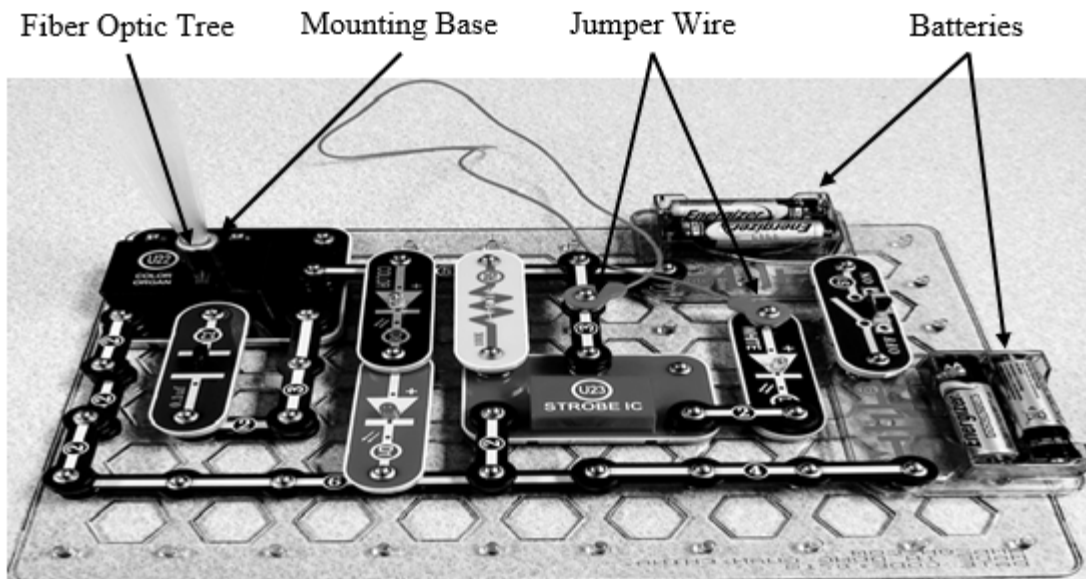


Figure 15. Completed Level Four Example

## ILLUSTRATED PARTS BREAKDOWN

### ILLUSTRATED PARTS BREAKDOWN SNAP CIRCUITS

MODEL: LIGHT,

ALL AVAILABLE PARTS FOR PROJECT(S) 1 - 182























Qty.	ID	Name	Symbol	Part #	Qty.	ID	Name	Symbol	Part #
1		Base Grid (11.0" x 7.7")		6SCBG	1	D6	White Light Emitting Diode (LED)		6SCD6
3	①	1-Snap Wire		6SC01	1	D8	Color Light Emitting Diode (LED)		6SCD8
6	②	2-Snap Wire		6SC02	1		Jumper Wire (black)		6SCJ1
3	③	3-Snap Wire		6SC03	1		Jumper Wire (red)		6SCJ2
1	④	4-Snap Wire		6SC04	1	M1	Motor		6SCM1
1	⑤	5-Snap Wire		6SC05	1		Spare Motor Top		6SCM1T
1	⑥	6-Snap Wire		6SC06	1		Glow Fan Blade		6SCM1FG
2	B1	Battery Holder - uses two (2) 1.5V type "AA" (not Included)		6SCB1	1		Disc Holder		6SCM1DH
1	C2	0.1μF Capacitor		6SCC2	1		Set of Disc Cutouts (6 pcs. / set)		6SCM1DS
1	C4	100μF Capacitor		6SCC4	1	Q1	PNP Transistor		6SCQ1
1	D1	Red Light Emitting Diode (LED)		6SCD1	1	Q2	NPN Transistor		6SCQ2

Figure 16. Illustrated Parts Breakdown Page One


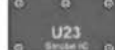


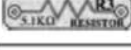

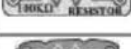













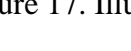

Qty.	ID	Name	Symbol	Part #	Qty.	ID	Name	Symbol	Part #
□ 1	Q4	Phototransistor		6SCQ4	□ 1	U23	Strobe IC		6SCU23
□ 1	R1	100Ω Resistor		6SCR1	□ 1	U24	Infrared Receiver		6SCU24
□ 1	R3	5.1kΩ Resistor		6SCR3	□ 1		Fiber Optic Cable		6SCFC
□ 1	R5	100kΩ Resistor		6SCR5	□ 1		Fiber Optic Cable Holder, clear		6SCFCHC
□ 1	RV	Adjustable Resistor		6SCRV	□ 1		Fiber Optic Cable Holder, black		6SCFCHB
□ 1	S1	Slide Switch		6SCS1	□ 1		Fiber Optic Tree		6SCFT
□ 1	S2	Press Switch		6SCS2	□ 1		Mounting Base (for fiber optic tree)		6SCFMB
□ 1	SP	Speaker		6SCSP	□ 1		Tower LED Attachment		6SCTOWER
□ 1	X1	Microphone		6SCX1	□ 1		Egg LED Attachment		6SCEGG
□ 1	U22	Color Organ		6SCU22	□ 1		Prismatic Film		6SCFILM
□ 1		Stereo Cable		9TLCST	□ 1		Red/Green/Blue Filters Set		6SCFRGB

Figure 17. Illustrated Parts Breakdown Page Two

## Appendix D: Simulated Technical Order (T.O.) HoloLens Copy

### 1. Review General Information before you begin

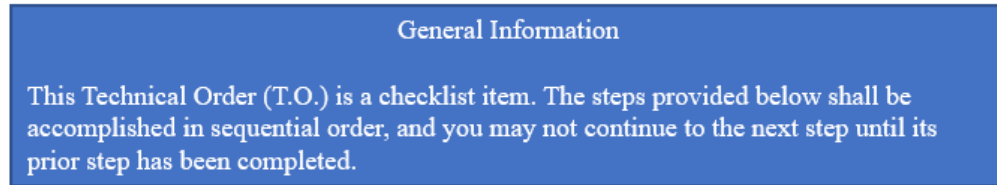


Figure 18. General Information (HoloLens)

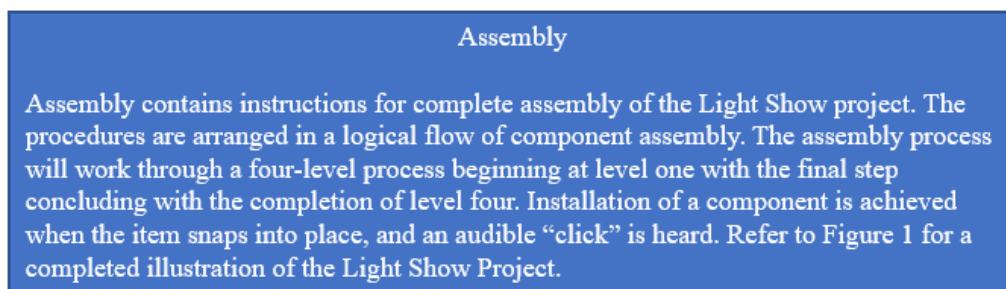


Figure 19. Assembly Information (HoloLens)

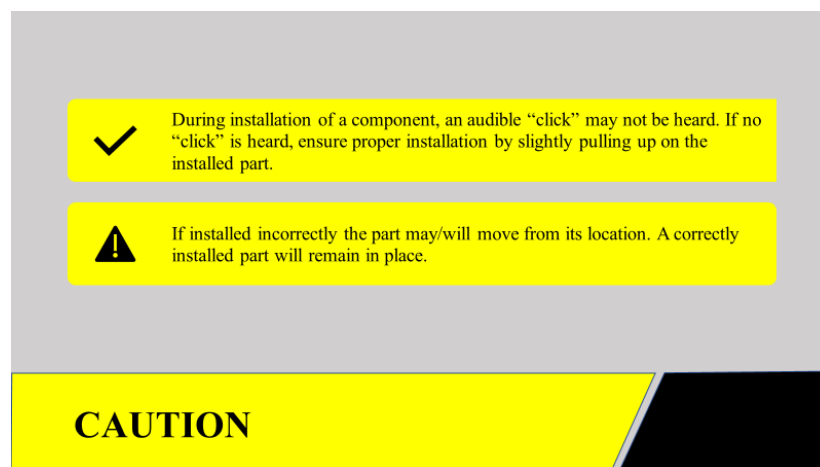


Figure 20. Task Cautionary Note (HoloLens)

2. Begin Assembly of Level One
3. Install Color Organ (U22) so the four corners are on A1, A3, C1, and C3 so that the box is on the left side of the board.
4. Align the first Battery Holder (B1) on B7, and B9 so that the battery compartment faces the top of the board and install.
5. Align the second Battery Holder (B1) on D9, and F9 so that the battery compartment faces the right side of the board and install.
6. Install the Strobe IC (U23) so the four corners are on D5, D7, E5, and E7 so that the Strobe IC box is facing the bottom of the board.
7. Install the White Light Emitting Diode (D6) on C8, and E8 so that the arrow is pointing to the bottom of the board.
8. Install a 6-Snap Wire on F1 and F6.
9. Install a 2-Snap Wire on D1, and E1.
10. Install a 2-Snap Wire on E2, and E3.
11. Install a 1-Snap Wire on D4.



12. Validate the placement of all Level One components (see Figure 21) and then begin assembly of Level Two.

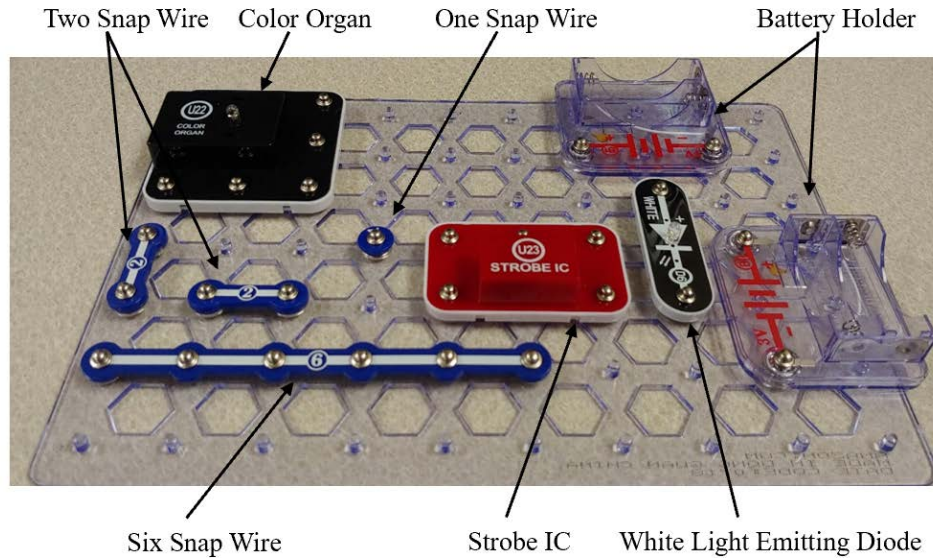


Figure 21. Completed Level One Example (HoloLens)

13. Begin Assembly of Level Two
14. Install the Red Light Emitting Diode (D1) on D4, and F4 so that the arrow is pointing to the bottom of the board.
15. Install the 0.1 $\mu$ F Capacitor (C2) on C2, and E2 so that the 0.1 $\mu$ F symbol towards the bottom of the board.
16. Install the Slide Switch (S1) on B9, and D9 so that the switch is toward the right side of the board.
17. Install a 5-Snap Wire on B3, and B7.
18. Install a 4-Snap Wire on F6, and F9.
19. Install a 3-Snap Wire on C3, and E3.
20. Install a 2-Snap Wire on C1, and D1.

21. Install a 2-Snap Wire on E1, and F1.
22. Install a 2-Snap Wire on E5, and F5.
23. Install a 2-Snap Wire on E7, and E8.
24. Install a 1-Snap Wire on D5.
25. Install a 1-Snap Wire on D6.
26. Validate the placement of all Level Two components (see Figure 22) and then begin assembly of Level Three.

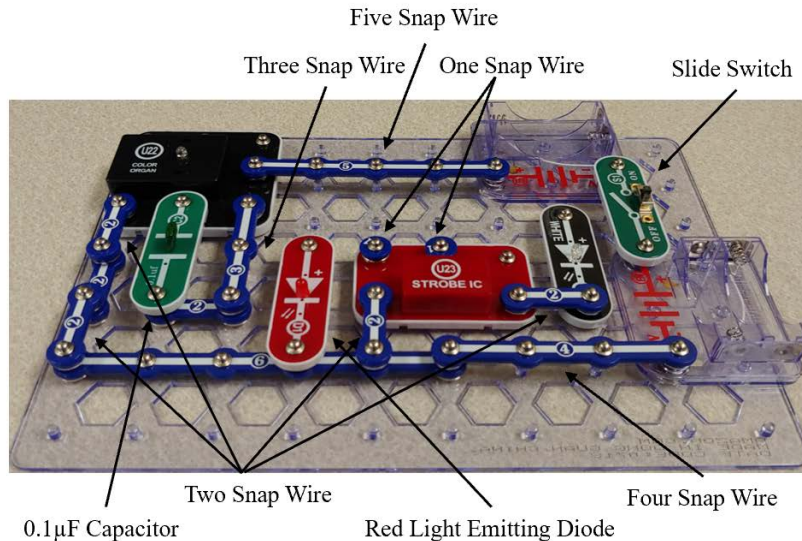


Figure 22. Completed Level Two Example (HoloLens)

27. Begin Assembly of Level Three
28. Install the Color Light Emitting Diode (D8) on B4, and D4 so that the arrow is pointing to the bottom of the board.

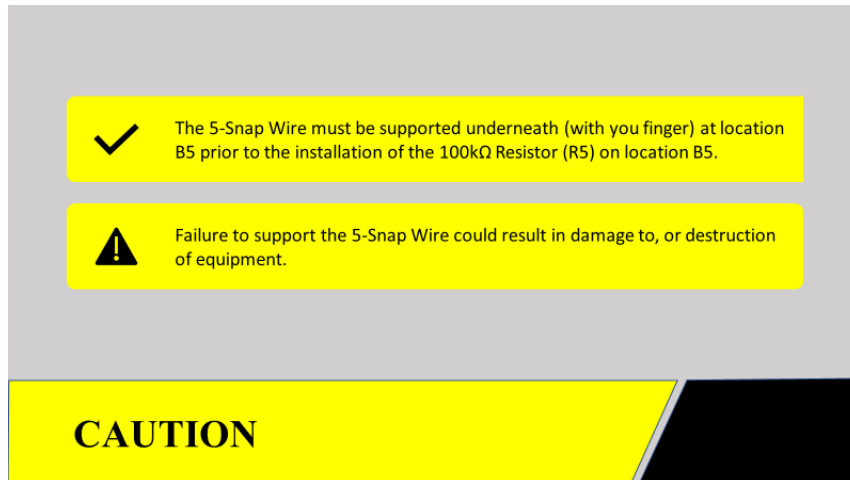


Figure 23. 5-Snap Wire Cautionary Note (HoloLens)

Install the 100k $\Omega$  Resistor (R5) on B5, and D5 so that the 100k symbol is toward the bottom of the board.

29. Install a 3-Snap Wire on B6, and D6.

30. Validate the placement of all Level Three components (see Figure 24) and then begin assembly of Level Four.



Figure 24. Completed Level Three Example (HoloLens)

31. Begin Assembly of Level 4

32. Install the Jumper Wire (Red) on C6, and C8.
33. Install the Mounting Base (MB) in the Color Organ (U22).
34. Install the Fiber Optic Tree (FOT) in the Mounting Base.
35. Install the first battery in Battery Holder #1 (B1) so that the top battery's positive terminal is facing the right side of the board.
36. Install the second battery in Battery Holder #1 (B1) so that the bottom battery's positive terminal is facing the left side of the board.
37. Install the first battery in Battery Holder #2 (B1) so that the right battery's positive terminal is facing the bottom of the board.
38. Install the second battery in Battery Holder #2 (B1) so that the left battery's positive terminal is facing the top of the board.
39. Validate the placement of all Level Four components (see Figure 25) and then inform the proctor you have completed the experiment.

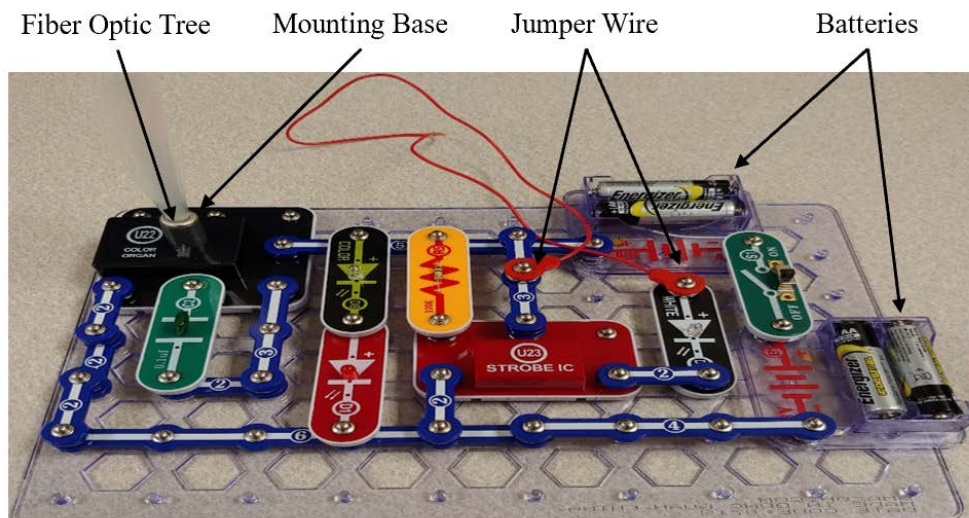


Figure 25. Completed Level Four Example (HoloLens)

# ILLUSTRATED PARTS BREAKDOWN

## ILLUSTRATED PARTS BREAKDOWN SNAP CIRCUITS

### MODEL: LIGHT,

### ALL AVAILABLE PARTS FOR PROJECT(S) 1 - 182




















Qty.	ID	Name	Symbol	Part #	Qty.	ID	Name	Symbol	Part #
□ 1		Base Grid (11.0" x 7.7")		6SCBG	□ 1	(D6)	White Light Emitting Diode (LED)		6SCD6
□ 3	(1)	1-Snap Wire		6SC01	□ 1	(D8)	Color Light Emitting Diode (LED)		6SCD8
□ 6	(2)	2-Snap Wire		6SC02	□ 1		Jumper Wire (black)		6SCJ1
□ 3	(3)	3-Snap Wire		6SC03	□ 1		Jumper Wire (red)		6SCJ2
□ 1	(4)	4-Snap Wire		6SC04	□ 1	(M1)	Motor		6SCM1
□ 1	(5)	5-Snap Wire		6SC05	□ 1		Spare Motor Top		6SCM1T
□ 1	(6)	6-Snap Wire		6SC06	□ 1		Glow Fan Blade		6SCM1FG
□ 2	(B1)	Battery Holder - uses two (2) 1.5V type "AA" (not Included)		6SCB1	□ 1		Disc Holder		6SCM1DH
□ 1	(C2)	0.1μF Capacitor		6SCC2	□ 1		Set of Disc Cutouts (6 pcs. / set)		6SCM1DS
□ 1	(C4)	100μF Capacitor		6SCC4	□ 1	(Q1)	PNP Transistor		6SCQ1
□ 1	(D1)	Red Light Emitting Diode (LED)		6SCD1	□ 1	(Q2)	NPN Transistor		6SCQ2

Figure 26. Illustrated Parts Breakdown Page One (HoloLens)



Qty.	ID	Name	Symbol	Part #	Qty.	ID	Name	Symbol	Part #
□ 1	(Q4)	Phototransistor		6SCQ4	□ 1	(U23)	Strobe IC		6SCU23
□ 1	(R1)	100Ω Resistor		6SCR1	□ 1	(U24)	Infrared Receiver		6SCU24
□ 1	(R3)	5.1kΩ Resistor		6SCR3	□ 1		Fiber Optic Cable		6SCFC
□ 1	(R5)	100kΩ Resistor		6SCR5	□ 1		Fiber Optic Cable Holder, clear		6SCFCHC
□ 1	(RV)	Adjustable Resistor		6SCRV	□ 1		Fiber Optic Cable Holder, black		6SCFCHB
□ 1	(S1)	Slide Switch		6SCS1	□ 1		Fiber Optic Tree		6SCFT
□ 1	(S2)	Press Switch		6SCS2	□ 1		Mounting Base (for fiber optic tree)		6SCFMB
□ 1	(SP)	Speaker		6SCSP	□ 1		Tower LED Attachment		6SCTOWER
□ 1	(X1)	Microphone		6SCX1	□ 1		Egg LED Attachment		6SCEGG
□ 1	(U22)	Color Organ		6SCU22	□ 1		Prismatic Film		6SCFILM
□ 1		Stereo Cable		9TLSCST	□ 1		Red/Green/Blue Filters Set		6SCFRGB

Figure 27. Illustrated Parts Breakdown Page Two (HoloLens)

## Appendix E: Institutional Review Board Approval for the Use of Human Volunteers in Research



**DEPARTMENT OF THE AIR FORCE**  
AIR FORCE RESEARCH LABORATORY  
WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433

MEMORANDUM FOR AFIT/ENS (BENJAMIN HAZEN)

FROM: 711 HPW/IR

SUBJECT: IRB Approval for the Use of Human Volunteers in Research

1. Protocol title: Implementation of Augmented Reality within Maintenance

2.	Protocol Number	Protocol Version	Risk Level
	FWR20190039H	V1.00	Minimal Risk

3.	Approval Date	Expiration Date	Re-approval Request Due by:
	13 December 2018	12 December 2019	12 November 2019

4. This study received Expedited Review using regulatory category: 32CFR219.110 (b)(7)
5. Summary: The purpose of this research is to conduct a qualitative usability evaluation of applying augmented reality technology into maintenance activities. This research will study the effectiveness and efficiency of an AR-enhanced task with the same non-AR enhanced task. Approximately 20 individuals will participate to help determine whether augmented reality enhances an individual's learning rate, whether it will decrease the time to complete a task and whether it will provide a lower error rate.
6. A waiver of documentation of consent has been granted for this research project as it meets the criteria outlined in 32 CFR 219.117 (c).
7. All inquiries and correspondence concerning this protocol should include the protocol number and name of the primary investigator. Please contact the 711 HPW/IR office using the organizational mailbox at [AFRL.IR.ProtocolManagement@us.af.mil](mailto:AFRL.IR.ProtocolManagement@us.af.mil) or by calling 937-904-8094 [DSN 674].

  
KIM E. LONDON, JD, MPH  
Chair, AFRL IRB

## Appendix F: Institutional Review Board Abbreviated Informed Consent

### Implementation of Augmented Reality within Maintenance

Abbreviated Informed Consent  
FWR20190039H v1.00

You are being asked to participate in a research study. The purpose of this research is to: assess the impacts of applying the AR technology into the maintenance environment related to learning rate, task completion time, and error rate.

The expected length of your participation is 1 hour.

If you participate in this research, you will perform two task. One of the task will be performed with paper instructions, and the other will be performed with a mixed reality interface instructional method. No personal information will be collected about you for this experiment.

Reasonably foreseeable risks to your participation are: eye soreness.

You are not expected to benefit directly from this research.

Your decision to participate in this research is voluntary. You can discontinue participation at any time without penalty or loss.

The researchers will take the following precautions to maintain the confidentiality of your data: the researchers will/will not collect any identifiers linked to you. No participant identifiers will be included in any publications. Electronic data will be password-protected.

The data may be accessed by the Department of Defense for auditing purposes.

If you have questions regarding the study, contact the Principal Investigator: (Major Benjamin Hazen / Associate Professor, AFIT/ENS 937-255-3636 x 4337) or ([benjamin.hazen@afit.edu](mailto:benjamin.hazen@afit.edu)). If you have questions regarding your rights as a research subject, contact the AFRL IRB: 937-904-8100 or [afrl.ir.protocolmanagement@us.af.mil](mailto:afrl.ir.protocolmanagement@us.af.mil).

Implementation of Augmented Reality within Maintenance  
FWR20190039H v1.00

AFRL IRB APPROVAL VALID 13 DECEMBER 2018 THROUGH 12 DECEMBER 2019



## Appendix G: Traditional T.O. Directives

### ***Air Force Institute of Technology***

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#### **Technical Order (T.O.) Project Completion Method**


Capt Terry Hebert

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Last Updated: 23-Feb-19



### **Information**



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- Complete the designed project with the T.O. and parts provided only.
- All information needed to complete the project is provided in the T.O.
- You will not be given any assistance once the task has started.

2

## Appendix H: AR-enabled T.O. Directives

### ***Air Force Institute of Technology***

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**Project Completion  
Mixed Reality (M/R)  
Method**

Capt Terry Hebert

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Last Updated: 25-Feb-19



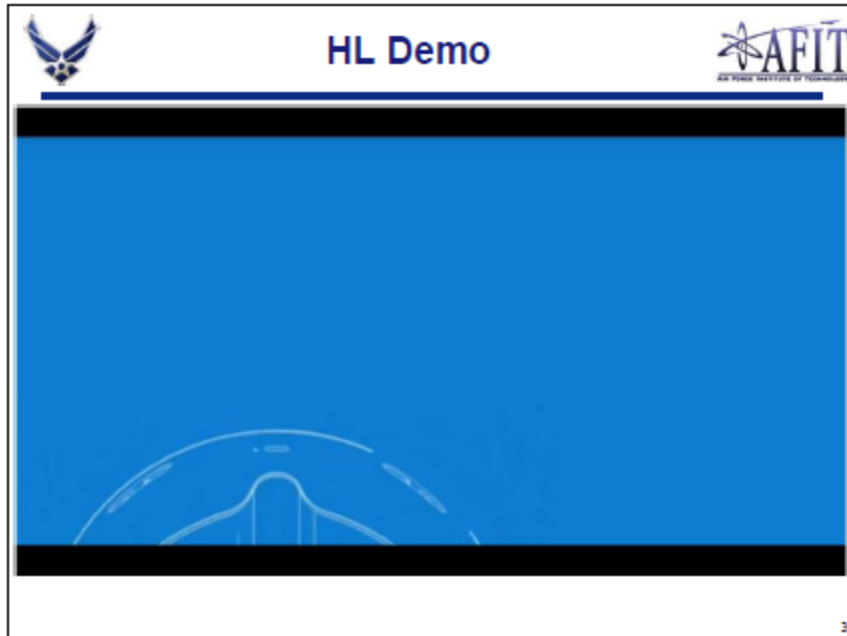
### **Information**



---

- **Complete the designed project utilizing the Microsoft HoloLens (HL), instructions and parts provided only.**
- **All information needed to complete the project is provided within the HL platform.**
- **You will not be given any assistance once the experimental task has started.**
- **A HL training session will be accomplished to ensure you understand how to operate the HL for this experiment.**

2



## HL Training

■ Once the HL is donned, you will see a white dot in the center of your screen, this is your "pointer".

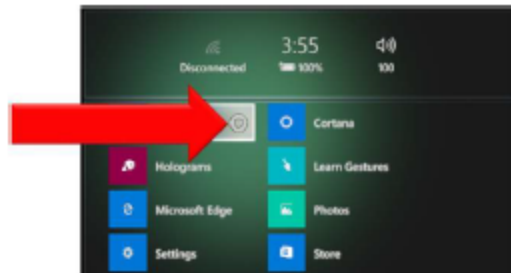
A screenshot of a Windows 8 Start menu interface. The background is dark. At the top, it shows "Disconnected", "2:39", and "100%". Below this is a "Key Cortana" section with a blue circular icon. The main area contains several app tiles: "e" (blue), "OneDrive" (blue), "Settings" (blue), "Photos" (green), "Store" (blue), "Maps" (red), and "Internet Explorer" (blue). A large red arrow points from the left towards the "e" tile. At the bottom, there are "Photos" and "Videos" icons. The slide number "4" is in the bottom right corner.



## HL Training



- When your hand is in view of the HL camera the white dot turns into a white circle. The white circle indicates the HL is tracking your hand movements and will respond to your hand gestures.



5



## HL Training



- The only hand gesture you will need to know for this project is the “air tap”. The air tap function is identical to pressing the left mouse button on a standard computer mouse.



1. Finger in the ready position



2. Press finger down to tap or click

How to perform an Air tap: Raise your index finger to the ready position, press your finger down to tap or select and then back up to release.

6



## HL Training



- To select an object place the white dot on the object you wish to select, raise your hand into the view of the HL (dot becomes a circle), and proceed to air tap.
- Note: For the HL to work correctly, you must look through the HL viewing window to receive the digital instructions. You will have an opportunity to experience the viewing window during the familiarization phase of the experiment.

7



## HL “Hands On” Training



- Before project initiation, you will be given a set of tasks to familiarize yourself with the HoloLense.
- During the familiarization steps, you may ask questions to aid in the utilization of the HoloLense.
- The familiarization steps will include a board alignment process to calibrate the experiment to you.
- Once the familiarization project is complete, you will proceed directly to the experimental project task under the proctors guidance.

8



## HL Training



- Once dawned, you may practice the air tap with the HL until you are comfortable with its operation. When performed correctly, an audible click will sound through the HL. During practice, you will not select any digital objects, but random locations throughout the room to familiarize yourself with the camera recognition process, and the sound a correct air tap makes.

9



## Project Navigation

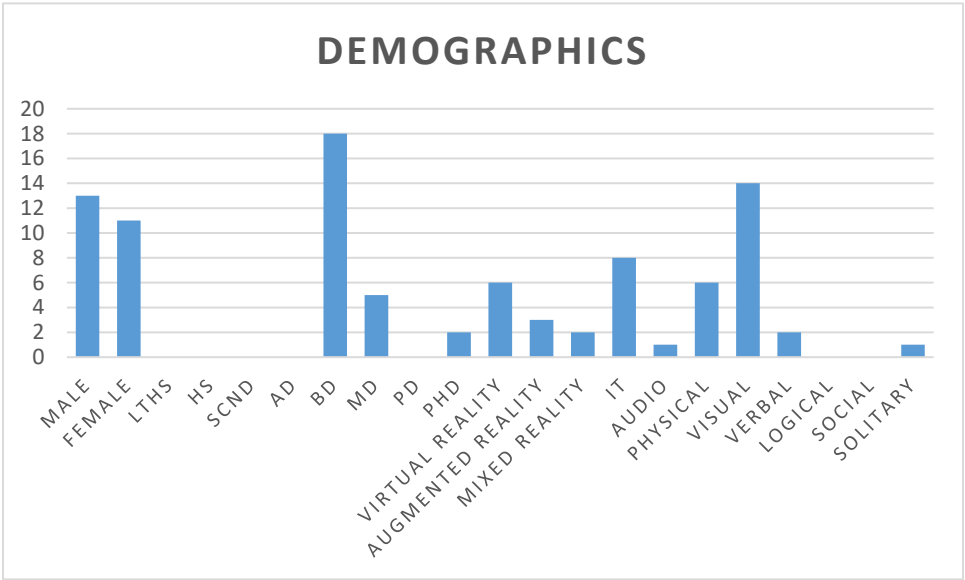


- When accomplishing the project and a step has been completed, air tap the next button to proceed to the next step.
- During the project, some steps will refer you to a photo note. To access the photo note select the “white” camera icon on a blue background, located just below the instructional step. The note will load to the right of the instructions.
- To close the photo note either air tap the “x” in the top right corner of the photo note or select “next” to proceed to the next step.

10

Appendix I: Demographics Information

Table 6. Demographics



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<b>14. ABSTRACT</b> The United States Air Force (USAF) expends significant resources to address the rise in aviation mishaps derived from an overworked, understaffed maintenance community, and high operational environment. Currently, paper-based technical orders (T.O.) are utilized by maintainers to accomplish aircraft inspections, servicing, and maintenance tasks. As technology advances, many civilian agencies have begun to leverage augmented reality (AR) to improve organizational proficiency. This research seeks to identify if the inclusion of AR within aircraft maintenance will positively or negatively affect maintenance task accuracy and completion time. A single variable randomized complete block design (RCBD), within-subject design of experiment (DOE) assesses the differences between a treatment group (AR-enabled T.O.) contrary to the control group (paper-based T.O.). Results conclude AR-enabled T.O.s designed from the AF perspective will reduce simple task errors, but will not impact total task completion time. Differentiation from prior findings, application specificity, will impact AR effectiveness and utilization within the organization employed. Additionally, experimental research revealed the need to address current AF infrastructure barriers before implementation of the technology within the organization.					
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